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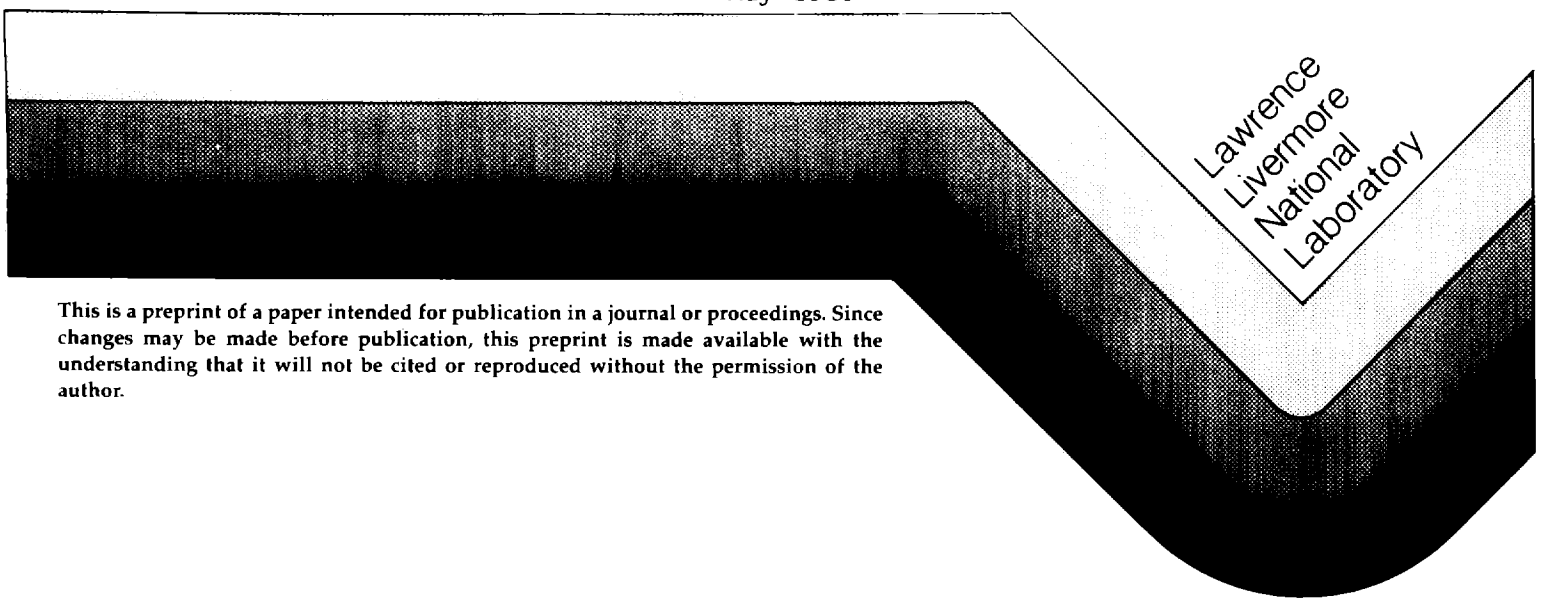

REACTION CROSS-SECTION CALCULATIONS USING NEW EXPERIMENTAL AND THEORETICAL LEVEL STRUCTURE DATA FOR DEFORMED NUCLEI*

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Abstract A technique for modeling level structures of odd-odd nuclei has been used to construct sets of discrete states with energies in the range 0 - 1.5 MeV for several nuclei in the rare-earth and actinide regions. The accuracy of the modeling technique was determined by comparison with experimental data. Examination was made of what effect the use of these new, more complete sets of discrete states has on the calculation of level densities, total reaction cross sections, and isomer ratios.

Several review papers have discussed the techniques employed in the calculation of neutron reaction cross sections for intermediate- or heavy-mass nuclei.[1] The elements of such a theoretical analysis include the use of a level density formulation in combination with the available experimental data on discrete states. In all discussions of statistical model formalism, the level density of residual states is acknowledged to play a crucial role because it determines the number of possibilities for decay of the excited compound nucleus.

For the purposes of understanding level density in a nucleus, experimental determinations of low-lying states usually produce level sets that are incomplete with respect to sampling states of all possible spins and parities due to the selectivity of the experimental probe. As an alternative to complete characterization of the discrete states of a nucleus up to some limiting excitation energy, modeling techniques offer some attractive features. When constructed properly, models may offer the ability to construct a reasonably complete level structure and may include the extrapolation of trends observed in neighboring nuclei.

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The physical concepts used here to model level structure apply to a restricted set of nuclei, namely those with a stable ground-state quadrupole deformation. Moreover, the modeling technique discussed in this paper applies to odd-odd nuclei. The ability to model these nuclei is important because of their inherent complexity and high level density at low excitations. The modeling technique was first described in papers by Struble,[2] Motz, et al.[2] and Scharff-Goldhaber et al.[3] They proposed that if the p-n residual interaction energy is small compared with the energy with which the odd nucleons are bound to the core, the excitation can be calculated by a simple extension of the odd-A model and the interaction energy can be treated later as a perturbation. Thus, in considering the coupling of two unpaired particles to a deformed core, the excitation energy of a given configuration is described as the sum of each of the odd-nucleon excitations. The excitation of an odd nucleon in a deformed nucleus can be treated theoretically by various versions of single-particle potential theory. For the purposes of this paper, however, the excitations are obtained from experimental data for neighboring odd-mass nuclei. In the actinide region[4], these data have been systematically surveyed by Chasman et al.

The effective moment of inertia for a rotational band can be expressed as the sum of three components: the moment of inertia of the even-even core plus increments from the addition of each of the two odd nucleons. With this model, effects due to Coriolis mixing that are peculiar to odd-odd nuclei are not included. However, those experimentally observed manifestations of Coriolis mixing in odd-A nuclei such as the compression or expansion of rotational spacing within a given band are included in the calculated effective moment of inertia for the odd-odd nucleus.

The excitation energies of levels in the odd-odd nucleus are calculated using the expression

$$E_I = E^p_{qp} + E^n_{qp} + (\hbar^2/2\theta_{\text{odd-odd}})\,[I(I+1)-K^2] - (1/2-\delta_{\Sigma,0})E_{GM} - \delta_{K,0}(-1)^I E_N \pi ,$$

where π denotes the parity of the states and is equal to ± 1 for positive or negative parity.

The E(GM) and E(N) terms in the equation, which are designated as the Gallagher-Moszkowski splitting and Newby shift, respectively, are functions of the effective neutron-proton residual interaction. For the actinide elements, these matrix elements have been calculated[5] recently assuming a zero-range central (δ) force between proton and neutron and a Nilsson-type potential. The one adjustable parameter needed to describe the strength of the δ force was obtained from a global fit of G-M splittings in the actinide region.

In Table 1 comparisons bewteen experimental and calculated bandhead energies and rotational parameters are summarized for three actinide nuclei where new experimental data have been obtained, 238Np, 250Bk, and 244Am, and for several rare-earth nuclides. The agreement for the actinide species is excellent, with bandhead energies deviating 22 keV and rotational parameters 5%, on the average. Corresponding deviations for the five rare-earth nuclei are 47 keV and 7%. As an illustration of the power of using empirical data obtained from neighboring odd-mass nuclei, a calculation was made with theoretical quasiparticle excitations for the odd-nucleons in 238Np taken from Nilsson potential calculations.[6] The average deviation (experimental minus calculated) for the 9 bandhead energies in 238Np was 163 keV; this can be compared with an average deviation of 29 keV obtained using empirical quasiparticle excitations. Similar differences are expected for the other nuclei listed in Table 1.

Thus, the evidence shows this modeling technique accurately reproduces experimental band-head energies and rotational parameters for these deformed nuclei. With this method, then, one can model all of the intrinsic single-particle excitations and rotational bands built on these excitations in any deformed odd-odd species where input data are available. Calculated level schemes can be extended to energies somewhat higher than the ranges given in Table 1, although it must be recognized that other kinds of excitations in these nuclei, e.g., vibrational motion and quasiparticle excitations involving more than two unpaired nuclei, are neglected in this limited approach.

Several applications of this modeling technique have proven to be useful. For example, ratios of cross sections for isomer production have been calculated[7] for the reactions 175Lu(n,γ) 176m,gLu and 237Np(n,2n)236m,gNp. The calculations were made with an LLNL version of the STAPRE statistical model code,[8] in which fission competition was not included. The Cook-modified, Gilbert-Cameron level density parameters[9] were employed, having been further adjusted to match discrete level information or to reproduce D_{ob} values where known. Below 1.5 MeV in each odd-odd product nucleus, the level density expression was replaced with a modeled set of discrete levels. The gamma-ray cascades leading to the ground-state and isomeric products were modeled for both the continuum and discrete-state regions. In order to achieve agreement with experiment, it has been found necessary to include in the modeled set many rotational bands (35-95), which are comprised of hundreds of levels with their gamma-ray branching ratios. It is essential that enough bands be included to produce a representative selection of K quantum numbers in the de-excitation cascade.

Table 1. Odd-odd nuclei in actinide and rare-earth regions: Comparison of experimental and calculated bandhead energies, rotational parameters, and G-M splittings.

Nucleus	Number of bands	Energy range (keV)	$\langle E_{exp}-E_{calc} \rangle$ (keV)	$\langle A_{exp}-A_{calc} \rangle$ (keV)	E_{GM} exp/calc
^{238}Np	9	0 - 345	29	0.14(3.2%)	1.18,0.87
^{244}Am	16	0 - 680	19	0.28(7.4%)	1.15,0.14,0.96
^{250}Bk	14	0 - 570	17	0.20(4.7%)	1.11,0.96, 2.87,1.39,1.32
^{160}Tb	8	0 - 380	41	0.61(8.1%)	1.03,1.07,1.13
^{166}Ho	10	0 - 560	47	0.74(8.7%)	0.80,1.08,1.31
^{170}Tm	5	0 - 450	63	0.46(5.2%)	2.04,0.98
^{176}Lu	12	0 - 840	58	1.0 (9.2%)	1.14,0.48, 1.01,0.91,0.39
^{182}Ta	7	0 - 270	24	0.47(3.9%)	0.94,0.97,1.14

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